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MECHANICAL RESPONSE OF COMPOSITE MATERIALS WITH THROUGH-THE-THICKNESS REINFORCEMENT

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ABSTRACT

An experimental investigation was conducted to identify the key geometrical parameters and quantify their influence on the mechanical response of through-the-thickness (TTT) reinforced composite materials. Composite laminates with TTT reinforcement fibers were fabricated using different TTT reinforcement materials and reinforcement methods and laminates were also fabricated of similar construction but without TTT reinforcement fibers. Coupon specimens were machined from these laminates and were destructively tested.

Through-the-thickness (TTT) reinforcement yarns enhance damage tolerance and improve interlaminar strength. Thick-layer composites with TTT reinforcement yarns have equal or superior mechanical properties to thin-layer composites without TTT reinforcement yarns. A significant potential exists for fabrication cost reduction by using thick-layer composites with TTT reinforcement yarns. Removal of the surface loop of the TTT reinforcement improves compression strength. Stitching provides somewhat higher mechanical properties than integral weaving.

OBJECTIVE AND APPROACH

The objectives of the present investigation, as presented in Fig. 1, are to identify the key geometrical parameters that influence the mechanical response of through-the-thickness (TTT) reinforced composite materials and, where possible, to quantify the influence of these key parameters on the mechanical response. The approach used to identify and quantify the effects of key geometrical parameters was based upon observations and destructive testing of coupon specimens, respectively. Composite laminates with TTT reinforcement fibers were fabricated using different TTT reinforcement materials and reinforcement methods. These laminates were microscopically examined to identify potential geometrical features that influence mechanical response. Coupon specimens were machined from these laminates and were destructively tested. Test results were compared with test results from materials of similar construction but without TTT reinforcement fibers.

Objective:

- Identify key geometrical parameters and quantify their influence on the mechanical response of through-the-thickness (TTT) reinforced composite materials.

Approach:

- Investigate specimens having different TTT reinforcement materials and reinforcement methods.
- Identify potential material and geometrical features that influences mechanical response.
- Investigate the influence of TTT reinforcement of materials having thick ply layers.

Figure 1

FEATURES OF TTT REINFORCEMENT THAT INFLUENCE MECHANICAL RESPONSE

There are four geometrical features of TTT reinforced composite materials that significantly influences their mechanical response, as shown in Fig. 2. These geometrical features are resin rich regions, in-plane fiber waviness, surface loop of continuous TTT reinforcement fibers and breakage of in-plane fibers.

- **Resin rich regions**
- **In-plane fiber waviness**
- **Surface loop of continuous through-the-thickness reinforcement**
- **Breakage of in-plane fibers**

Figure 2

PHOTOMICROGRAPHS OF STITCHED AND INTEGRALLY WOVEN COMPOSITE MATERIAL

The resin rich regions identified in Fig. 3 were created by the inclusion of TTT reinforcement fibers. The stitch yarn creates a small inclusion around each TTT reinforcement penetration. The TTT reinforcement fibers of the integrally woven material create resin channels because the integrally woven TTT reinforcement fibers separate adjacent in-plane yarns. It is well understood that changes in fiber volume fraction can change the mechanical properties of composite materials (ref.1). Therefore, it is reasonable to believe that resin rich regions created as an artifact of inserting TTT reinforcement fibers could influence both laminate stiffness and strength.

Fiber waviness in composite laminates has also been identified as a mechanism that can adversely influence compression strength (ref. 2). The vertical portion of the TTT reinforcement fibers creates in-plane fiber waviness of the in-plane reinforcement fibers, as observed in Fig. 3, for both stitched and integrally woven TTT reinforced laminates. The amplitude of the waviness is approximately equal to the diameter of the TTT reinforcement fibers which is generally greater than the fiber waviness found in non-textile composite laminates.

When TTT reinforcement fibers penetrate in-plane yarns, such as in the stitched laminate depicted in Fig. 3, the penetration by the needle and stitching yarn can result in breakage of in-plane fibers. With proper processing the majority of the in-plane fibers at stitch penetration are pushed aside as the needle penetrates the preform. Generally, less than 5 percent of the in-plane fibers at the penetration site are broken (ref.3). No significant breakage of in-plane fibers occurs for integrally woven TTT reinforced materials because the TTT reinforcement does not penetrate the in-plane yarns and hence little or no breakage of in-plane reinforcement fibers occurs in the weaving process.

(Figure 3 appears on the next page.)

PHOTOMICROGRAPHS OF STITCHED AND INTEGRALLY WOVEN COMPOSITE MATERIAL

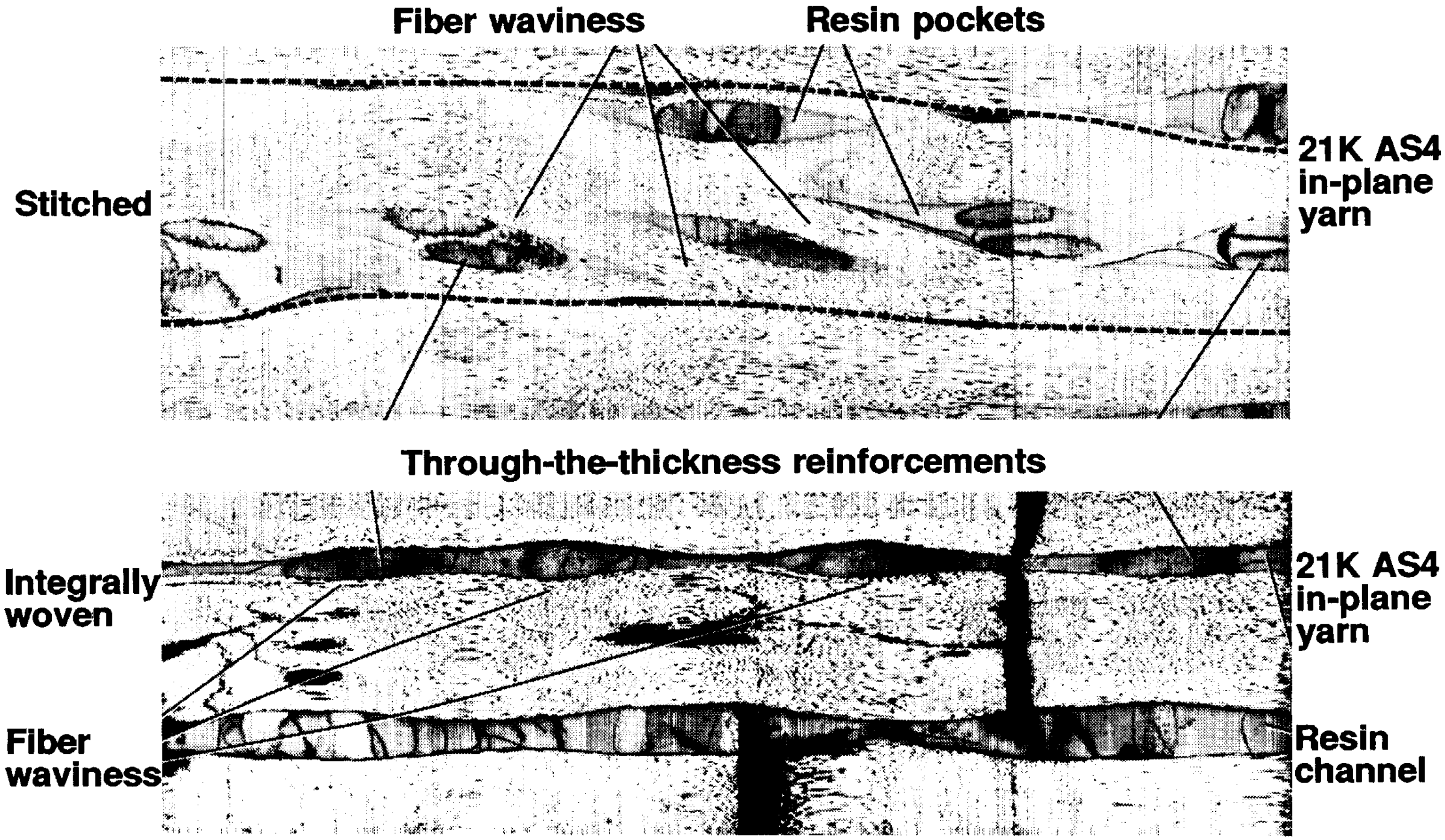


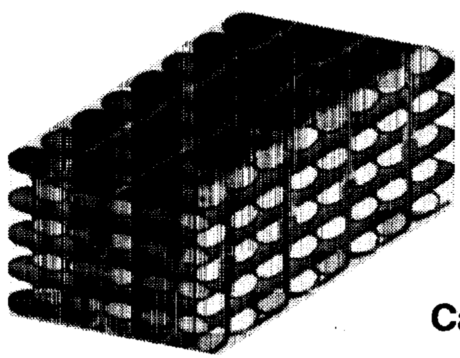
Figure 3

KINKED IN-PLANE SURFACE YARN

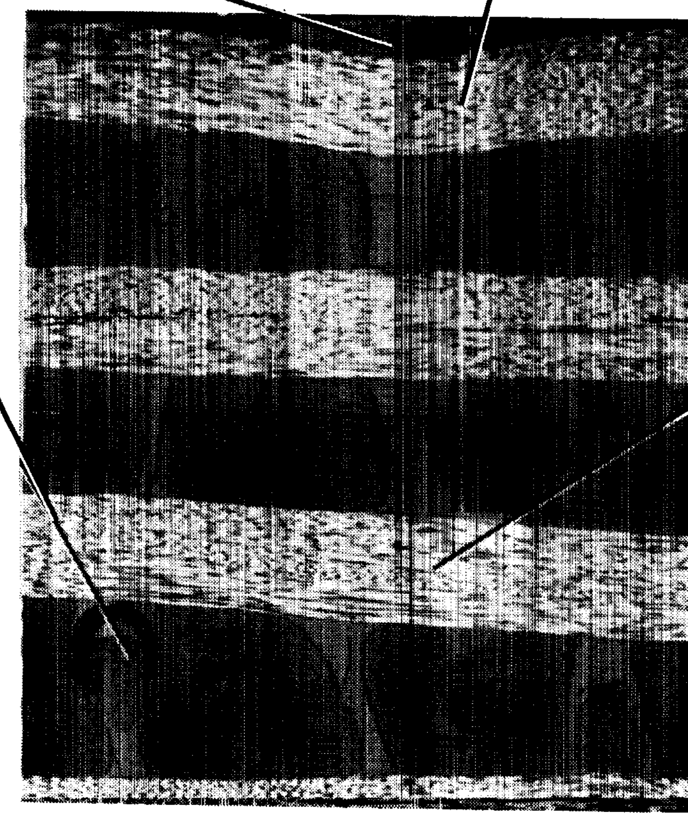
Both the stitched and integrally woven materials studied in this investigation use continuous TTT reinforcement fibers. Between successive TTT fiber penetrations, a part of the TTT reinforcement fibers extends across the laminate's surface. The portion of the TTT reinforcement fibers that lies on the surface is referred to as the surface loop, see Fig. 4. When the preform is infiltrated and processed into a composite part, the surface loop of the TTT reinforcement fibers is forced into the surface of the laminate causing a kinking or bending of the laminate's in-plane fibers near the laminate surface. The magnitude of the kinking or bending of the in-plane fibers is a function of the diameter of the surface loop yarn and the compaction pressure used during consolidation. Only the layers of in-plane fibers near the surface of the laminate are influenced by the surface loop. That is, the layers near the center of the laminate are not kinked or bent by the surface loop.

(Figure 4 appears on the next page.)

KINKED IN-PLANE SURFACE YARN



Integrally woven
3-D preform



Photomicrograph of laminate cross section

Figure 4

MATERIALS INVESTIGATED

All laminates studied in this investigation were fabricated using Hercules, Inc. AS4 carbon fiber with Hercules, Inc. 3501-6 epoxy resin and were approximately 0.64 cm thick. See Fig. 5. The stacking sequence for all laminates consisted of variations of a 0/90 cross-ply stacking sequence. However, the per ply thickness, stacking sequences, inclusion of TTT reinforcements, TTT reinforcement method and TTT reinforcement material differed between laminates. The 0/90 stacking sequence was chosen so that a direct comparison between materials with stitched and integrally woven TTT reinforcement fibers could be made. Three different laminates were fabricated without TTT reinforcement fibers to quantify the influence of in-plane fiber architecture and TTT reinforcement fibers on the mechanical response. Two of these laminates were fabricated from unidirectional prepreg material. Their stacking sequences are $[(0/90)_2/0/(0/90)_5/0/(0/90)_3/0]_s$ and $[(0_5/90_5)_2/0_3]_s$ and they are referred to herein as the thin-layer and thick-layer material, respectively. The third material without TTT reinforcement, referred to as the uniweave material, was fabricated from a nine layer stack of dry uniweave fabric that was infiltrated and cured to form the composite laminate. This uniweave fabric has approximately 99 percent of its carbon fibers oriented in the fabric's warp direction. The remaining one percent of the fibers are fine denier glass yarns used to hold the carbon warp yarns together. The glass yarns are oriented in the fabric's fill direction. Each layer of the uniweave fabric is approximately equal to five layers of unidirectional prepreg tape material. The uniweave fabric is composed of 21K-filament carbon yarns with a yarn spacing of approximately 5 per cm. The thick-layer and uniweave materials are similar in layer thickness and construction.

All laminates with TTT reinforcement fibers have the same ply orientation as the uniweave material, that is [0/90/0/90/0/90/0/90/0]. Two different types of TTT reinforcement yarn were used, namely carbon and Kevlar yarns. The carbon yarn is a Toray T-900-1000A stitching yarn and the Kevlar yarn is a 1100 denier Kevlar-49 yarn. Both the stitched and integrally woven materials were made with the same number and spacing of TTT reinforcement yarns. The stitched preforms were produced using uniweave fabric. All laminates fabricated with TTT reinforcement fibers were fabricated by stitching or integral weaving. Both stitching and integral weaving are referred to herein as continuous TTT reinforcement processes. Simulated tufted TTT reinforcement was produced by machining the surfaces of stitched or integrally woven laminates to remove the surface loop of the TTT reinforcement fibers. The simulated tufting TTT reinforcement is referred to herein as a discontinuous TTT reinforcement process.

AS4-3501-6, 0.64 cm thick

Laminates without through-the-thickness (TTT) reinforcement
- Thin layer - $[(0/90)_2/0/(0/90)_5/0/(0/90)_3/0]_S$
- Thick layer - $[(0_5/90_5)_2/0_3]_S$
- Uniweave - [0/90/0/90/0/90/0/90/0]

Laminates with TTT reinforcement
[0/90/0/90/0/90/0/90/0]

TTT fiber	TTT method
Carbon	Continuous
Kevlar	Stitched
	Woven
	Discontinuous
	Simulated tufting

Figure 5

PREFORM ARCHITECTURE

Three different TTT reinforced preform architectures were used in this study, as seen in Fig. 6. The stitched preforms were created by stacking nine layers of uniweave fabric in a 0/90 orientation and the stack was stitched using a modified through-the-thickness lock stitch in orthogonal rows and columns oriented parallel and perpendicular to the 0 degree direction of the preform, respectively. The integrally woven preforms were produced as a single unit on a loom. The in-plane warp and fill yarns were not interwoven. The nine layers of fabric were held together by the TTT reinforcement yarns woven in both the warp and fill directions. The TTT reinforcement yarns were inserted and wrapped around a catcher yarn in the center of the preform and returned to the surface. Therefore, the TTT reinforcement yarn in the integrally woven material was actually composed of two yarns, a yarn originating from the upper surface and one originating from the lower surface. The simulated tufting material was produced by machining away one half of the upper and lower outer surface layers from the stitched and integrally woven cured composite laminates.

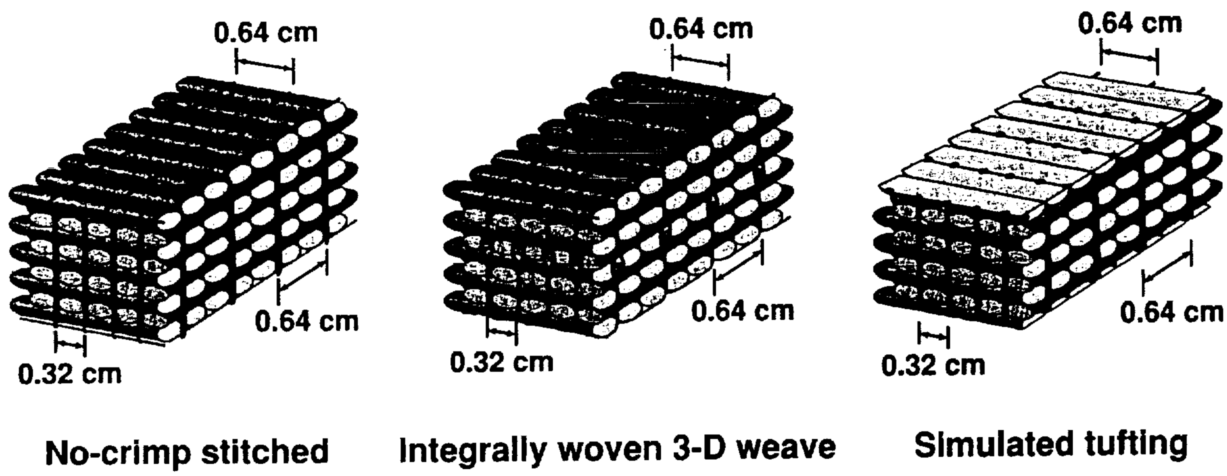


Figure 6

TEST SPECIMENS

Three different test specimens were used to evaluate the mechanical response of the different materials. They were the compression-after-impact (CAI) specimen, the short-block-compression (SBC) specimen and the multi-span-beam (MSB) specimen, as depicted in Fig. 7. The CAI and SBC specimens were machined from laminates such that the direction of the applied load coincided with the 0 degree direction of the laminate stacking sequence. The MSB specimens were machined from laminates such that the 90 degree direction of the laminate stacking sequence was parallel to the length of the specimen.

The CAI specimen was used to evaluate the damage resistance and residual compression strength of a damaged panel. The CAI specimen was 12.7 cm wide by 25.4 cm long. A 0.127-cm-diameter aluminum ball was shot at the center of each CAI specimen with approximately 42J of energy. Back-to-back strain gages were bonded to each CAI specimen. Each CAI specimen was then mounted into a side-supported compression test fixture and statically compressed to failure.

The SBC specimen was used to evaluate the undamaged compression strength of the material. The SBC is 3.81 cm wide by 4.45 cm long. Each specimen was instrumented with back-to-back strain gages. The SBC specimens were mounted in a compression test fixture without side supports and a static compression load was applied until the specimen failed.

The MSB specimens were used to evaluate, in a qualitative manner, the interlaminar strength of the material. The MSB test consists of an upper and lower load introduction structure which makes contact with the specimen at five locations across the width of the specimen. The width of the specimen is 2.54 cm and the length is 12.7 cm. A static compression load is applied to the specimen until failure.

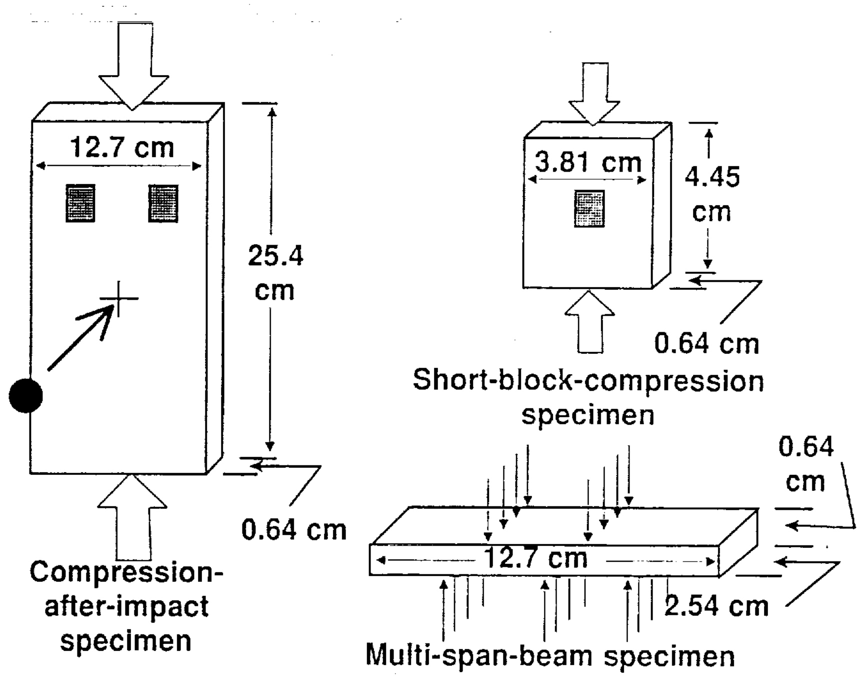


Figure 7

EFFECTS OF TTT REINFORCEMENT ON COMPRESSION STRENGTH

Short-block-compression tests were performed on the thin-layer, thick-layer, uniweave materials as well as the carbon and Kevlar TTT reinforced stitched and integrally woven materials. The highest compression strength was obtained from the thin-layer material followed by the uniweave, thick-layer materials and the materials with TTT reinforcement yarns. See Fig. 8. The difference in strength between the three materials without TTT reinforcement yarns is related to the architecture of the materials. Increasing layer thickness produces a corresponding increase in the magnitude of interlaminar stresses; therefore the thin-layer material should have higher compression strength than the thick-layer material. The thick-layer and uniweave materials have similar layer thickness, however the uniweave had higher strength. This difference in strength is attributed to the glass fill yarn which partially intertwines each warp yarn in the uniweave material and produces some intralaminar reinforcement.

All of the specimens with TTT reinforcement yarns have significantly lower undamaged compression strength than those materials without TTT reinforcement yarns. The stitched material exhibited somewhat higher undamaged compression strength than the integrally woven materials. The strength difference is attributed to the reduced amount of kinking or bending of the in-plane fibers adjacent to the surface loop formed by the needle yarn in the stitched material. The needle yarn used in the stitched material was a small denier yarn which produced less kinking or bending of the in-plane yarns when the preform was processed into a composite part. The type of reinforcement yarn in the TTT reinforced laminates had no influence on compression strength.

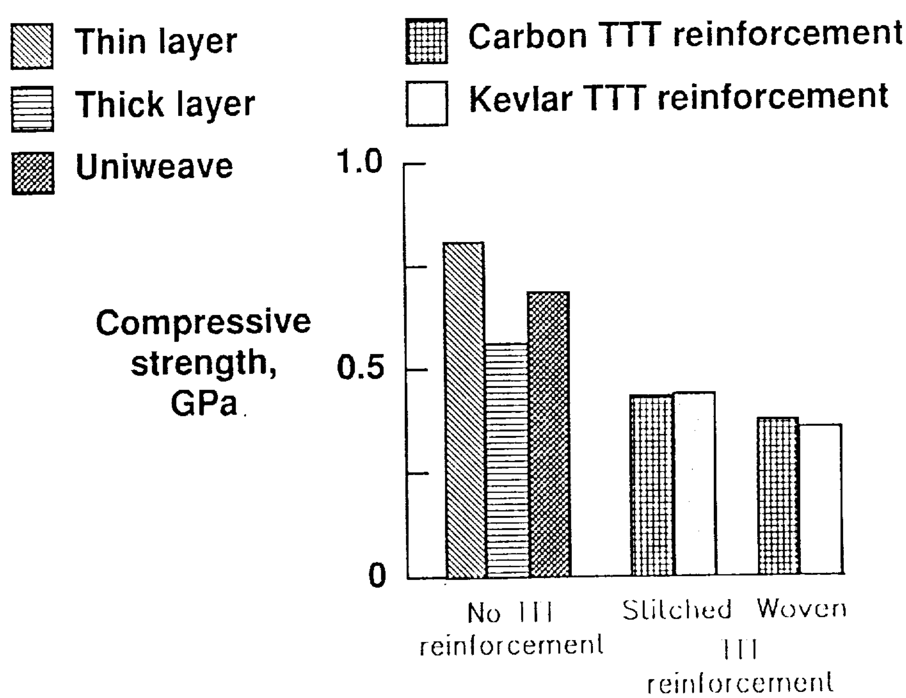


Figure 8

FAILURE MODES OF SHORT-BLOCK-COMPRESSION SPECIMENS

The compression failure mode for the thin-layer, thick-layer and uniweave materials was primarily delamination which precipitated a transverse shear failure, as shown in Fig. 9. This failure mode was caused by interlaminar stresses. All materials with TTT reinforcement yarns exhibited a transverse shear failure mechanism because the TTT reinforcement yarns increase the interlaminar strength of the laminate which suppresses the delamination failure mechanism.

(Figure 9 appears on the next page.)

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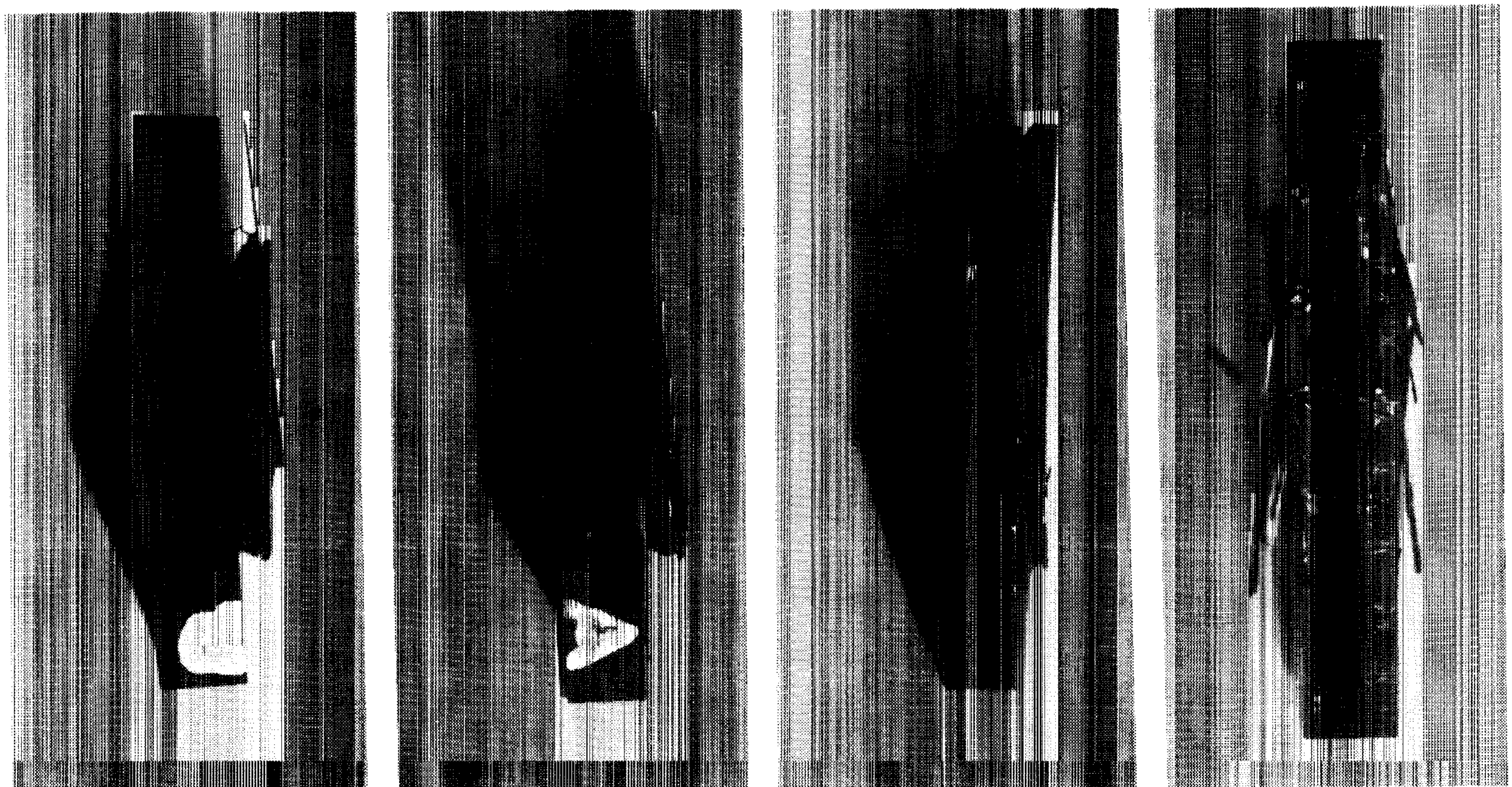
FAILURE MODES OF SHORT-BLOCK-COMPRESSION SPECIMENS



"Thin" "Thick" "Uniweave" Kevlar woven TTT reinforcement

Figure 9

INFLUENCE OF TTT SURFACE LOOP ON COMPRESSION STRENGTH

Short-block-compression tests were conducted on stitched and integrally woven composite laminates. One-half of the specimens had one-half of their surface layers machined away to simulate tufting. The simulated tufted specimens are referred to herein as those "without TTT surface loop". In all cases removal of the TTT reinforcement surface loop and the associated kinked or bent in-plane fibers resulted in higher compression strength. See Fig. 10. Compression strength was based upon the actual cross-sectional area of the specimen, that is the reduced area in the case of machined specimens. The axial-load-carrying capability is primarily due to the 0 degree fibers. Approximately 12 percent of the 0 degree fibers were removed in the machining process because the outer layers were oriented in the 0 degree direction. Since the machining produced a net increase in strength, the 0 degree fibers that were machined away were ineffective in carrying a compressive load.

The stitched material with the TTT surface loop had higher compressive strength than the integrally woven material. However, after the surfaces were machined there was little or no difference in compression strength between the stitched and integrally woven materials. The stitched materials had the surface loop on the bobbin yarn surface created by the carbon or Kevlar TTT reinforcement yarns, whereas the surface loop produced on the needle yarn surface was made with a much smaller denier yarn. The surface loops produced in the integrally woven materials were produced using the same type carbon or Kevlar yarn on the outer surfaces. Therefore, more in-plane fibers in the integrally woven materials were kinked or bent than in the stitched materials, hence the lower compression strength for the integrally woven materials.

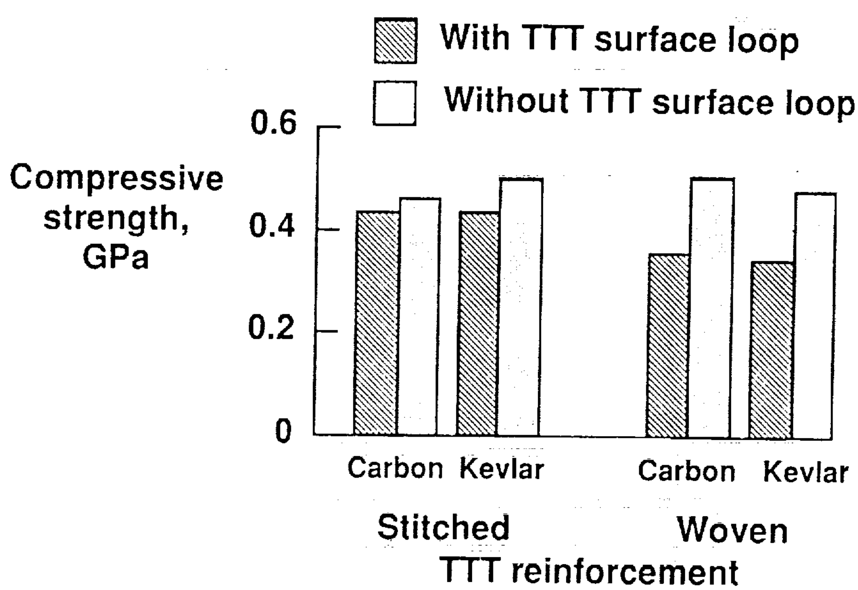


Figure 10

FAILURE MODES OF SBC AND CAI SPECIMENS

The failure modes of SBC and CAI specimens having TTT reinforcement yarns with and without the surface loop of the TTT reinforcement yarn are shown in Fig. 11. Both the unmachined (with surface loop) and machined (without surface loop) specimens have similar transverse shearing failure modes.

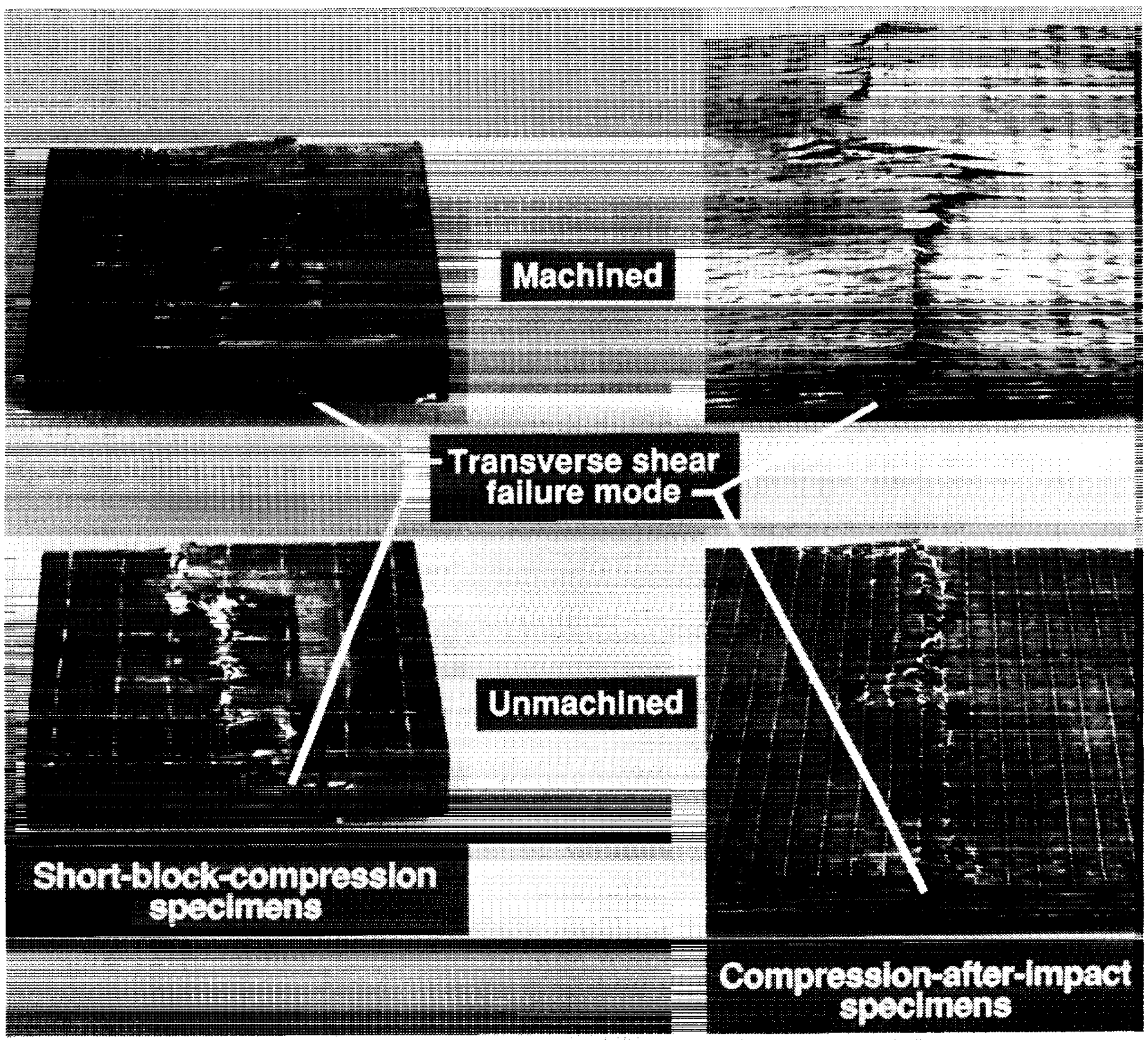


Figure 11

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EFFECTS OF TTT REINFORCEMENT ON COMPRESSION STRENGTH OF IMPACTED PANELS

The materials with TTT reinforcement yarns exhibited nearly twice the CAI strength as materials without TTT reinforcement yarns, as shown in Fig. 12. The typical failure mechanism of the CAI panels is controlled by the interlaminar strength of the material. Inclusion of TTT reinforcement yarns improves the interlaminar normal and shear strengths of the material and produces a higher CAI strength. Stitched materials have slightly higher CAI strengths than the integrally woven materials. This trend is consistent with the undamaged compression strength of these materials. The thin-layer material exhibited higher CAI strength than either the uniweave or the thick-layer materials. The relative magnitude of the CAI strength of materials without TTT reinforcement yarns was consistent with the undamaged compression strength for these materials.

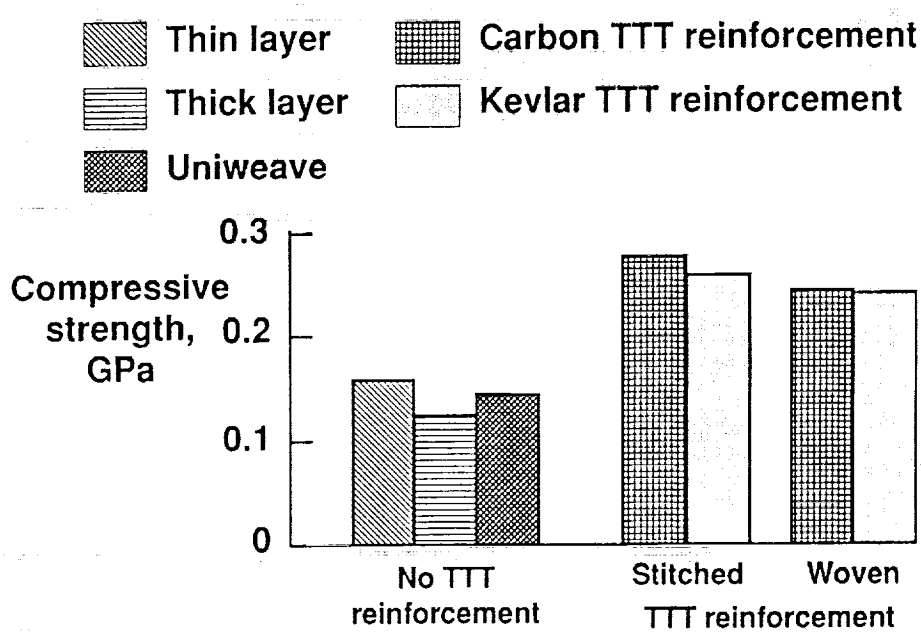

Figure 12

EFFECTS OF TTT SURFACE LOOP
ON COMPRESSION STRENGTH OF IMPACTED PANELS

Neither the CAI strength nor the impact-induced damage area were affected by the removal of the TTT surface loop, as shown in Fig. 13. All panels were impacted at approximately 42J of energy; however the panels with the surface loop removed were 11 percent thinner. It was initially expected that the thinner panel would have a greater damage area due to impact but the results indicate that this was not the case. These results suggest that the surface loop has no positive influence on the CAI strength. Futhermore, the surface loop has no influence on the damage containment because the damage area of the specimens with and without a surface loop was approximately the same.

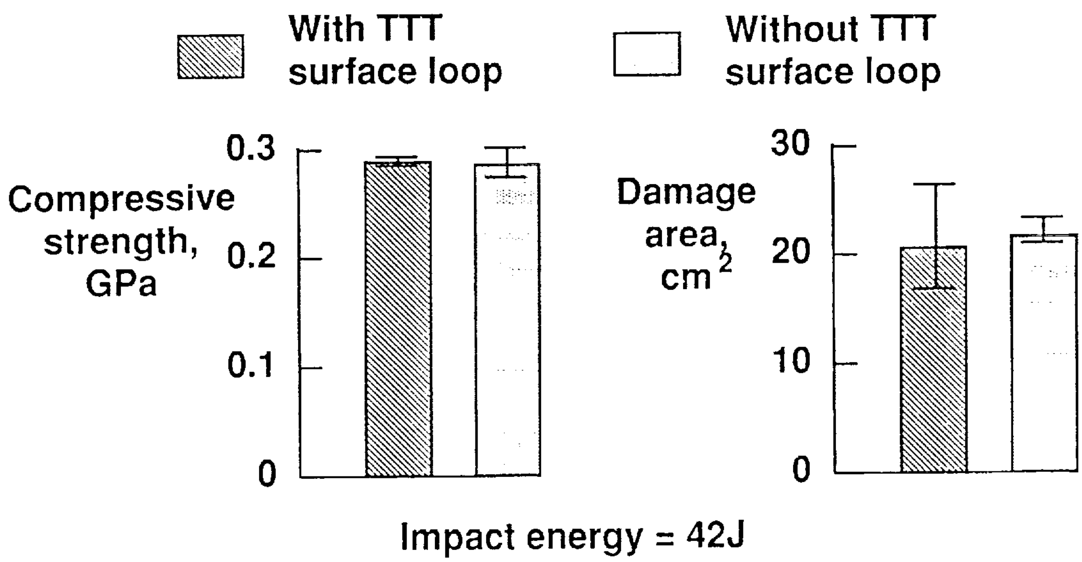

Figure 13

EFFECTS OF TTT REINFORCEMENT ON MULTI-SPAN-BEAM STRENGTH

The MSB strength of the thin-layer material is considerably higher than the MSB strength of either the thick-layer or the uniweave materials as shown in Fig. 14. This ordering of strength is consistent with the compression and CAI strength for these materials without TTT reinforcement yarns because the failure mechanism is induced by interlaminar stresses. However, the MSB strength of the thick-layer material with carbon TTT reinforcement yarns was 60 percent higher than the thick-layer and uniweave materials and was 90 percent of the MSB strength of the thin-layer material. These results suggest that when properly designed, thick-layer material with TTT reinforcement yarns can be used in lieu of thin-layer materials. A significant cost savings (material and processing) can be realized by using thick-layer material with TTT reinforcement yarns.

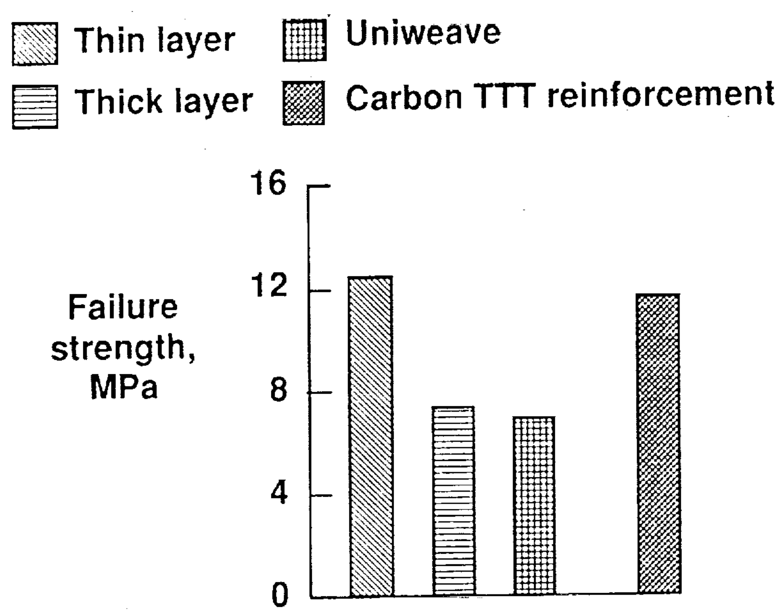

Figure 14

INFLUENCE OF TTT REINFORCEMENT SURFACE LOOP
ON MULTI-SPAN-BEAM STRENGTH

The surface loop had no effect on MSB strength for either type of TTT reinforcement or reinforcement method as seen in Fig. 15. This result is reasonable because the region of high interlaminar shear and the initial failure site are in the center of the laminate. The surface loop influences the mechanical properties of the in-plane fibers along the outer surface of the specimen. Therefore, it is reasonable to expect that the surface loop has no influence on the MSB strength.

The MSB strength of the stitched material is consistently higher than the MSB strength of the integrally woven material. The MSB failures always initiated in the interior of the beam in a 90 degree ply or in one of the resin pockets. The integrally woven materials have larger resin pockets than the stitched material and have TTT yarn loops around a catcher yarn along the specimen's centerline. It is suspected that the larger resin pockets and the presence of the catcher yarns are responsible for the lower MSB strength of the integrally woven materials.

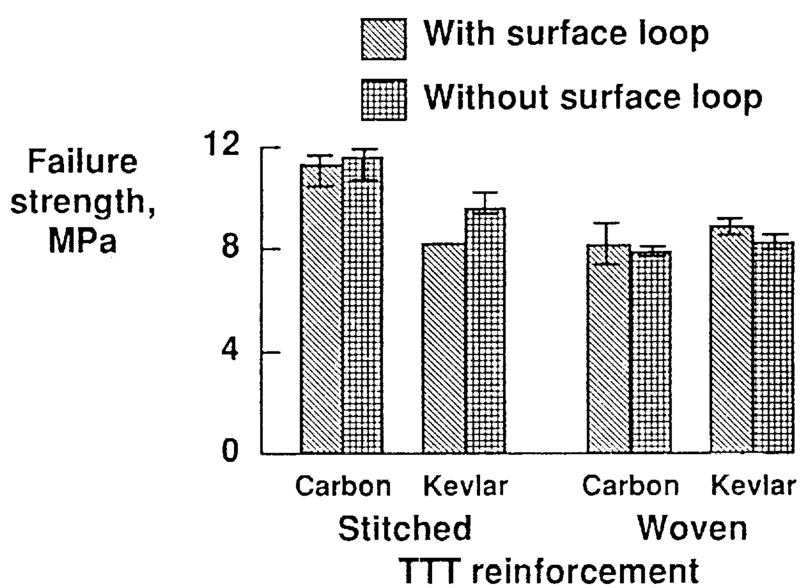

Figure 15

CONCLUDING REMARKS

An experimental investigation was conducted to identify the key geometrical parameters and to quantify their influence on the mechanical response of through-the-thickness (TTT) reinforced composite materials. Composite laminates with TTT reinforcement fibers were fabricated using different TTT reinforcement materials and reinforcement methods. These laminates were microscopically examined to identify potential geometrical features that influence mechanical response. Coupon specimens were machined from these laminates and were tested to failure. Test results were compared with test results from materials of similar construction but without TTT reinforcement fibers. The concluding remarks are summarized in Fig. 16 and discussed further below.

Through-the-thickness reinforcement yarns enhance the damage tolerance and improve interlaminar strength of composite materials. However, TTT reinforcement yarns in composite materials cause a reduction in undamaged compression strength. The reduction of undamaged compression strength due to incorporating TTT reinforcement yarns in composite materials is a result of local resin rich regions, in-plane fiber waviness, surface loop of the TTT reinforcement yarn kinking or bending the in-plane fibers, and breakage of in-plane fibers.

The thick-layer composites studied in this investigation with TTT reinforcement yarns have mechanical properties that are equal to or superior to thin-layer composites without TTT reinforcement. Thick-layer materials can be fabricated from large filament count yarns at a lower cost than with small filament count yarns. Cost of large filament count reinforcement yarns is substantially less than the cost of small filament count reinforcement yarns. Fewer thick layers of material are required to produce a part than are parts produced from thin-layer materials. The reduced number of layers of material reduces part layup cost. Therefore, there is a significant potential cost savings when using thick-layer composites and large filament count yarns.

The stitched materials evaluated in this investigation had different denier yarn for the needle and bobbin yarns. The needle yarn was a smaller denier TTT reinforcement yarn than the bobbin yarn. The smaller denier needle yarn kinked or bent the inplane fiber less than the larger denier bobbin yarn. Since the inplane surface yarns adjacent to the needle yarn are kinked and bent less, then their compression strengths are degraded less. The TTT reinforcement yarns in the integrally woven materials were of the same denier as the larger denier TTT reinforcement yarn in the stitched material. The outer surfaces of the integrally woven laminate were equally influenced by the surface loop of the TTT reinforcement yarns. Therefore, stitched laminates provide somewhat higher mechanical properties than integral weaving.

- Through-the-thickness reinforcement enhances damage tolerance and improves interlaminar strength.
- Thick layer composites with TTT reinforcement have equal or superior mechanical properties to thin layer composites without TTT reinforcement. (Potential exists for fabrication cost reductions.)
- Removal of surface loop improves compression strength.
- Stitching provides somewhat higher mechanical properties than integral weaving.

Figure 16

REFERENCES

1. Jones, R. M. 1975. Mechanics of Composite Materials. New York, NY: McGraw-Hill Book Co.

2. Shuart, M. J., "An Analysis of Shear Failure Mechanisms for Compression-Loaded $[\pm\Theta]_S$ laminates", Journal of Composite Materials, Vol. 23, March 1989.

3. Portanova, M. A., Poe, C. C. and Whitcomb, J. D., "Open Hole and Post-Impact Compression Fatigue of Stitched and Unstitched Carbon/Epoxy Composites", NASA TM 102676, June 1990.